Design and Implementation of High Power Factor LED Driver with Hot Swap, Smart Output Voltage Regulation and Dimming Control

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Abstract: In this paper, a high power factor LED driver with hot swap, smart output voltage regulation and dimming control is proposed. The dimming control is used to change LED brightness. During converter is working, the hot swap function supply users to remove and insert LED module. The smart output voltage can regulate quickly and rightly output voltage in different number of LED series connection. The system consists two stages, one is 50 W flyback converter which is used as power factor corrector, it is input source is 110-220 V, PF (power factor) is about 0.994. The other is Boost DC/DC converter, it can offer 35-60 V of output voltage. Finally, a prototype has been built and tested. The simulation and experimental results are shown to verify the feasibility of the proposed method.

Key words: Hot swap, smart output voltage regulation, dimming control, flyback converter, boost converter.

1. Introduction

In general, a LED driver system contains two stages, one is PFC (power factor correction) to improve poor power quality, such as current harmonics, voltage harmonics, voltage flicker, voltage spikes and current surges, and the other is driver and dimming control. PFC in power converter with a LC filter, π-type filter, valley-fill filter or a harmonic trap filter power factor circuit in front stage to achieve the object early, as shown in Fig. 1 [1, 2]. These methods are passive corrections, filter with large volume does not only meet the needs of light, thin, short, small requirements, but also serious and current harmonic distortion can not meet regulatory requirements. Table 1 shows the advantages and defects of passive PFC.

On the other side, due to active PFC system using PWM (pulse width modulation) technique so that the input current and voltage waveform possess same phase and meet the requirements specification [3-6]. In a wide range of AC voltage (Universal Full Range, 85-265 V), its power factor can achieve above 90% whether heavy load or light load. Thus, it not only enhances the user power quality, but also reduces input current THD.

Fig. 2 shows the characteristic of the LED forward voltage vs. forward currents, it can be seen that when the voltage across the LED exceed the conducted voltage, then forward current begins to flow through the LED, and the forward current will rapid increase while the conducted voltage slightly varied.

Fig. 3 shows the relation of the LED forward current vs. lumens, it can be seen that the forward current and lumens are linearly relationship. That is, the forward current which flows through the LED increase, the brightness is larger.

With the improvement of LED energy dissipated, heat is important. If the dissipated heat is not well done,
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![Passive PFC circuits](image1)

**Fig. 1** Passive PFC circuits.

<table>
<thead>
<tr>
<th>Passive PFC circuits feature.</th>
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<tbody>
<tr>
<td>Advantage</td>
</tr>
<tr>
<td>1. Circuit structure is simple, low cost</td>
</tr>
<tr>
<td>2. Easy design</td>
</tr>
<tr>
<td>Defect</td>
</tr>
<tr>
<td>1. Too large and heavy weight</td>
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<tr>
<td>2. Poor power factor, low efficiency</td>
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**Table 1** Passive PFC circuits feature.

![Characteristic of the LED forward voltage vs. forward currents](image2)

**Fig. 2** Characteristic of the LED forward voltage vs. forward currents [7].

![Relation of the LED forward current vs. luminous intensity](image3)

**Fig. 3** Relation of the LED forward current vs. luminous intensity [7].

it will result from changing the characteristics of LED, as shown in Fig. 4. It can be seen that the forward voltage of the LED with 20 mA forward current will greatly reduce while ambient temperature rise.

![Relation of forward voltage vs. ambient temperature](image4)

**Fig. 4** Relation of forward voltage vs. ambient temperature [7].

Due to the output voltage of traditional LED driver is fixed, user only string the LEDs according to the output voltage of LED driver, this will cause very inconvenient for extending the LED number. For solving the above problem, a high power factor LED driver with hot swap, smart output voltage regulation and dimming control is proposed in this paper. It will greatly improve the practicality of LED illumination.

### 2. Multi-functional LED Driver

The functions of the proposed LED driver contain LED dimming, LED module hot swap and smart voltage regulation. LED dimming can self-adjust the brightness of LED module by user for saving energy. LED module hot swap function can easily plug-in or plug-out the LED module under uninterrupt power to improve the operational convenience. The driver voltage can be adjusted rapidly and accurately by smart voltage regulation while user plug-in the different count LED module. The detail illustration is shown as follows.

#### 2.1 LED Dimming Control

Linear dimming is the one of traditional LED dimming scheme, as shown in Fig. 5. A resistor series to LED module and used to control the brightness of LED by change the resistor value. Its advantages are simple and low cost, but its efficiency is very poor due to power loss of resistor.

Fig. 6a shows the pulse dimming scheme, it using the power switches to generate the current pulse and change the LED brightness. The principle of pulse
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Fig. 5  Linear dimming scheme.

(a) Series linear dimming  (b) Parallel linear dimming

Fig. 6  LED dimming circuit.

(a) Series linear dimming  (b) Parallel linear dimming

dimming is that the LED forward current is to transform to pulse form, and the pulse width can be adjusted. The more pulse width, the higher LED average current, and the more LED brightness. On the contrary, if reducing the pulse width, the LED brightness will darken.

When the LED lights continue, the waste heat generated will increase the environment temperature. From Fig. 4, it can be seen that LED is a kind of temperature components, its forward voltage will differ under different ambient temperatures, so LED drivers need the function of detecting current flowing through the LED. Therefore, a series-wound resistor is need to sense current, as shown in Fig. 6b. When the ambient temperature increases, the current flows through the LED also increase the voltage across the series-wound resistor also rise. The power converter can reduce the output voltage by feedback control, let the current flowing through the LED can meet the specifications.

2.2 LED Module Hot Swap

Fig. 7 shows an example of 5 series 20 W LED module which has two lighting methods. One is used a 100 W power convert, as shown in Fig. 7a, the system must turn off the power when replace the LED module, thus, it will influence the other active LED module. So the other method (5 set 20 W power converter) is used to improve above defect, as shown in Fig. 7b, but thus system has more complicated circuit and cost.

Fig. 7  Sketch map of traditional LED driver.

In this paper, a LED module hot swap scheme is proposed. LED module hot swap allows users to replace the faulty module under the case of uninterrupt supply as shown in Fig. 8. In Fig. 8, a power switch is added to avoid causing spikes and transient current surges which will cause the LED module and power converter damage. Due to the hot swap function, a faulty module can directly pulled down, and a new module can be plugged in, the power converter is under the uninterruptible supply the system.

2.3 Smart Output Voltage Regulation

Output voltage of traditional LED driver is fixed; user can only series the LED number according to the specification. It can not random series or parallel the LED number. For improving this drawback, intelligent output voltage regulation function is designed in this paper. Its function can base on the series number of LED to adjust the output voltage to a suitable voltage. For example, the output voltage is automatically adjusted to 38.4 V under series 12 LED, while output voltage is 51.2 V under serial 16 LED, as shown in Fig. 9.

3. System Structure

The system structure includes two stages, one is AC/DC converter which is used as power factor corrector, and its input source is AC 110-220 V. The other is DC/DC converter, it can offer 35-60 V of output voltage, as shown in Fig. 10.

3.1 Active Power Factor Circuit

Power factor circuit is used to PFC. In much circuit structure, flyback converter is very popular due to the
advantages of simple structure, low cost, with electrical isolation. Therefore, flyback converter is used to power factor correction in this paper as shown in Fig. 11 [8].

The operational principle of flyback converter is as follows. When switch $S_w$ is turned on, the current flow is shown in Fig. 12a, $i_{L_m}$ is increase and energy is saved in $L_m$. Due to the polarity is reversed, diode $D$ is turned off, and the needed energy of load is supplied by output capacitor $C$. When $S_w$ is turned off, the polarity of secondary side of transformer is reversed, diode $D$ is turned on, and the energy saved in $L_m$ will transfer to output capacitor $C$ and load, as shown in Fig. 12b. Thus, the voltage stress of switch $S_w$ is $V_{in} + (N_1/N_2)V_o$ and the voltage stress of diode $D$ is $V_o + (N_2/N_1)V_{in}$.

For reducing the current ripple, EMI and component voltage stress, boundary turn on mode control scheme, which is provided by ST L6562, is used in the system.

### 3.2 DC/DC Converter

In this paper, the functions of DC/DC converter is dimming, hot-swap, and output voltage regulation, in non-isolated structure, buck, boost and buck-boost possess the least number of components. Because the power switches of are buck and buck-boost floating drives, so the boost converter is used in this paper, as shown in Fig. 13.

The operational principle of boost converter is as follows. When switch $S_w$ is turned on, the energy is saved in inductor $L$, and diode $D$ is turned off, the needed energy of load is supplied by output capacitor $C$, as shown in Fig. 14a. When $S_w$ is turned off, diode $D$ is turned on, and the inductor $L$ release energy to capacitor $C$ and load $R$, as shown in Fig. 14b. So the voltage stress of Switch $S_w$ and diode $D$ is $V_o$.

For achieving the functions of dimming control, hot swap and smart voltage regulation, a MCU PIC 18F4520 is used in the system.
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3.3 Multi-functional LED Module Driver

Fig. 15 shows the connection diagram of boost converter and LED module. The number of LED can be adjusted in a certain range of voltage. R1 and R2 can random design, when $V_{a1}$ is rised to highest voltage, it must to keep less than 5 V, and $V_{b1}$ is the voltage of across R3 whose value is $V_{b1}/I_{LED}$. $I_{LED}$ is the conducted current of LED.

Fig. 16 shows the flow chart of system operation, it illustrate as follows:

1. System initial and MCU transfer a 10% PWM pulse to $S_1$, $V_o = 35$ V. Due to LED module not plug in yet, $V_o = 0$;

2. When LED module is plugged in, the $V_o$ is transmitted to A/D2 and the duty cycle if PWM 2 is changed to full-open;

3. $V_o$ is transmitted to A/D3 and enlarge the duty cycle of PWM 1 simultaneously. Boost converter begins to step up voltage untie $V_o \geq 0.5$ V;

4. The duty cycle of PWM 2 is controlled by the value of A/D1 converter. Check $V_{a1} = 0$ and $V_{a2} = 0$? If no, set $Z_2 = 1$ and transmit PWM 2 signal to $S_3$. Next,
check $V_{b1} > 0.6 \text{ V}$ and $V_{b2} > 0.6 \text{ V}$? If yes, reduce $V_o$ voltage to avoid the LED over-current;

(5) Check again $V_{a1}$ and $V_{a2} = 0$? If not, return to step 4. If yes, the duty cycle of PWM 1 is adjusted to 10% and stop transmits the PWM 2 pulse to $S_2$, return to step (1).

4. Experimental Results

Fig. 17 shows the integrated circuit of system hardware, a 40 W multi-functional LED driver is implemented, and the system electrical specifications and component list are shown in Table 2.

The first-stage is flyback converter whose input voltage is AC 110-220 V, output power is 50 W (32 V/1.56 A), and the ST L6562 [9-11] is used as controller. The second-stage is boost converter whose output power is 40 W, and using the PIC 18F4520 to control. When the LED module is not plugged in, the duty cycle of boost converter switch is 10%, output voltage is 35.4 V, as shown in Fig. 18a. When the LED module is plugged in and the series number of LED is 18, the output voltage is 56.48 V, and duty cycle is 43.5%, as shown in Fig. 18b.

Fig. 19 shows the rise time and recovery time of different plug-in series number of LED module, it can be seen that the more series number of LED module, the longer rise and recovery time. For example, when the series number of LED module is 18 sets, its rise time is 0.45 s, and recovery time is 0.1 s, that is, the LED module lighted needs 0.5 s.

### Table 2  Electrical specifications and component list.

<table>
<thead>
<tr>
<th></th>
<th>Flyback</th>
<th>Boost</th>
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</thead>
<tbody>
<tr>
<td>Input voltage ($V_i$)</td>
<td>AC 110-220 V</td>
<td>32 V</td>
</tr>
<tr>
<td>Output voltage ($V_o$)</td>
<td>32 V</td>
<td>35-60 V</td>
</tr>
<tr>
<td>Output current ($I_o$)</td>
<td>1.56 A</td>
<td>1.14-0.667 A</td>
</tr>
<tr>
<td>Switching frequency ($f_s$)</td>
<td>&gt; 40 kHz</td>
<td>50 kHz</td>
</tr>
<tr>
<td>Inductor ($L$)</td>
<td>1 mH</td>
<td>1.2 mH</td>
</tr>
<tr>
<td>Capacitor ($C$)</td>
<td>4,400 uF</td>
<td>470 uF</td>
</tr>
<tr>
<td>Power switch ($S$)</td>
<td>STP11NM80</td>
<td>SANYO 2SK1430</td>
</tr>
<tr>
<td></td>
<td>$V_{DS}: 800$ V</td>
<td>$V_{DS}: 100$ V</td>
</tr>
<tr>
<td>Diode ($D$)</td>
<td>STPS20S100CT</td>
<td>STPS20S100CT</td>
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<tr>
<td>Core</td>
<td>EI30</td>
<td>EI30</td>
</tr>
</tbody>
</table>

![Fig. 17 Integrated circuit of system hardware.](image)

![Fig. 18  Output voltage and duty cycle waveforms of boost converter.](image)
Fig. 20 shows the LED dimming signal and the LED current waveforms. It can be seen that the current flowing the LED is zero during dimming signal is 0%, so the LED module does not light up, as shown in Fig. 20a. When dimming signal is 50%, the current flows the LED is a 50% duty cycle pulse, the average current is 9.52 mA, as shown in Fig. 20b. Fig. 20c shows the dimming signal is 100%, and the average current 19.04 mA.

Multi-module hot swap operation is one the key point of this proposed system. When the first LED module is plugged-in and lighted, as shown in Fig. 21a, the second LED module is then plugged-in, as shown in Fig. 21b. When the first LED module is faulty and plugged-out, it can be seen from Fig. 21c that the second module is not affected.

Fig. 22 shows the input current waveforms of flyback converter operated under 110 V and 220 V, respectively. It can be seen that the current and voltage is in phase. Fig. 23 shows the power factor of flyback converter operated under AC 110 V and 220 V, and measured at different output power. It can be seen that the highest power factor is 0.994 and 0.948 during the input voltage is 110 V and 220 V, respectively.

Fig. 24 shows the efficiency of flyback converter operated under different output power. It can be seen that the maximum efficiency is 84.9% during the AC 110 V.

Fig. 25 shows the measured input current harmonics at the input voltages of 110 V and 220 V. It is obvious that the current harmonics are satisfied with the IEC 61000-3-2 class C specification.

Fig. 26 shows the efficiency of boost converter operated under different output power. It can be seen that the maximum efficiency is 85.1% in full load.

5. Conclusions

In this paper, a high power factor LED driver is implemented with hot swap, smart output voltage regulation and dimmer control, and the dimming pulse
width can be adjusted from 0 to 100%. The output voltage of boost converter is 35-60 V. It can connect multiple LED modules which series number from 12 to 18 pcs, and user can random adjust in this range. The power factor of flyback converter is 0.994 at the AC 110 V and maximum efficiency of 84.9%. The maximum efficiency of DC/DC boost converter is 85.3%. Finally, experimental result is used to verify the feasibility of the proposed system and verify the system satisfied with market demand.
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References


